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LEWIS RESEARCH CENTER OF NASA**

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ABSTRACT

Construction details and performance data of special-purpose, superconductive magnets planned and in use at the Lewis Research Center of NASA are presented in this paper. The magnets described include (1) a pair of 2.5-tesla force-reduced toroids, 30 centimeters in diameter with a winding cross section 2.5 centimeters in diameter; (2) a 15-centimeter-bore magnetic bottle with 5-tesla mirrors, a 2.5-tesla center coil, and a quadrupole Ioffe coil producing a cusp field; and (4) a 6.25-centimeter-bore, 10-tesla solenoid.

INTRODUCTION

The Lewis Research Center has a need for large-volume, high field-strength magnets for use in its program on advanced space propulsion and power concepts, and also for its research in solid-state, plasma, and low-temperature physics. The development of such magnetic fields has been in progress for about 9 years. The work in conventional water-cooled and cryogenically cooled, but not superconducting, magnets has been described previously.^(1 to 5) These references describe the magnets, built and used at Lewis Research Center, which produce magnetic fields up to 20 teslas in an 11-centimeter bore and 16 teslas in a 30-centimeter bore. These magnets are now in use in several research programs.

Enormous amounts of electrical power are required for room-temperature electromagnets, and the operation time is limited in cryogenically-cooled, but not superconducting, magnets. The operating time limitation results because a large supply of cryogen must be available for cooling the coils if boiling heat transfer is used. Superconductive coils, on the other hand, require a liquid-helium environment. After the coils are charged, the helium boiloff rate is limited to the heat leaking into the dewar. This amount can be made very small by careful design and construction of the dewar; hence, operation of the coils is very economical.

The NASA Lewis Research Center has a large and efficient helium recovery and liquification system⁽⁶⁾ with a capacity of 300 liters of liquid helium per hour. Thus, the helium environment can be quite easily provided for superconductive coils.

Studies^(7 to 8) have shown that, for such possible space applications as magnetohydrodynamic power generation and thermonuclear power generation and propulsion, the only practical solution to the required magnetic fields is the superconductive magnet. As NASA's primary space propulsion and power research laboratory, the Lewis Research Center is especially interested in the development of superconductive magnets. The Status of the Lewis Program will be described in this paper.

Force-Free Toroids

The concept of the force-free magnet has been known and used since

the early days in the production of high-field magnets. Pioneers such as Kapitza⁽⁹⁾ and Cockcroft⁽¹⁰⁾ used the principle of uniform hydrostatic pressure throughout the magnet windings. In more recent times, the concept has been used in various laboratories concerned with the construction of high-intensity fields of large volume for thermonuclear research.^(11 and 12)

It can be easily demonstrated, of course, that no finite magnet is truly force free. Nevertheless, a toroid can be wound so that everywhere the conductor is nearly parallel to the field. In this case, $\vec{j} \times \vec{B}$ is small, and there is a reduced force on the conductor.

For superconductors, however, there is another advantage of winding the conductor parallel to the local magnetic field. Experiments have shown that superconductors carry more current when placed in longitudinal fields than when placed in transverse fields. Sekula⁽¹³⁾ and Cullen⁽¹⁴⁾ made measurements which show that the critical current is strongly influenced by the angle that the conductor makes with the field. These and other investigations showed that the current enhancement can be as much as a factor of 10 or more. In figure 1, The variation of the critical current with the angle made by the conductor with the magnetic field is shown for two different Type II superconductors, niobium zirconium and niobium stannide.

The two NASA force-reduced toroids are wound with niobium-0.25 zirconium, which has the short-sample critical current-field curves shown in figures 2(a) and (b). In figure 2(b), the current is at a

maximum when the conductor is placed in a 2.5-tesla field parallel to the direction of the current. The NASA toroids were designed to operate in a self-field of this magnitude to take advantage of this increased performance, an enhancement factor of about 8. Not all this enhancement was realized, however, in the wound coils. The critical currents of the two coils were 110 and 108 amperes, respectively.

High-Field, Large-Bore Solenoid

As mentioned before, very intense magnetic fields have many potential applications. Such fields are most easily produced by solenoids. For this reason, when it was decided to produce a 15-tesla field in a 15-centimeter bore, a solenoid design was specified. To produce a field of this magnitude in such a volume by conventional, water-cooled magnets would require many megawatts of power; thus, the advent of high-current high-field superconductors made such a magnet feasible.

The solenoid was built for the Lewis Research Center by the Radio Corporation of America. It was wound with a ribbon conductor consisting of niobium stannide vapor deposited on a substrate of stainless steel. At the present, niobium stannide (Nb_3Sn) has the highest critical field (>22.0 T) and the highest critical temperature (18.4°K) of any superconductor. Indeed, extensive research during the past several years has failed to find a superconductor that approaches niobium stannide in the magnitude of these two parameters. This material, together with its substrate, is exceedingly strong and can be manufactured in a

range of sizes to carry a large range of currents. Physical properties of a typical ribbon used are presented in table I.

The ribbon material is silver plated for stabilization of the superconductor and for protection of the superconductor during handling. The ribbon can be wound, unwound, and rewound on a small radius (~ 1 cm) without damage to the performance of the superconductor. The short-sample performance is shown in figure 3 where the critical current I_c is plotted as a function of the external field. In figure 3⁽¹⁵⁾ are shown the critical-current magnetic-field data for two types of Nb_3Sn ribbon that were manufactured for specific field ranges. Figure 4 presents data for exceptionally high-field material that can be used to wind the portion of a coil which is in the highest field.

Since large hoop stresses are encountered in magnet coils of this size (15-cm bore), the effect of stress on the superconductor is an important parameter. Figure 5 shows the effect of stress on copper- and silver-plated niobium stannide ribbon samples that were oriented transversely to the magnetic field with the field parallel to the plane of the ribbon. This relation of current to field is of major concern in large solenoids, since the innermost turns of the conductor are in exactly this orientation. The critical current density as a function of stress was relatively constant for both types of platings (fig. 5). The critical current density of the copper-plated ribbon increased slightly with stress (fig. 5(b)). Generally, the increase was less than

5 percent. With all the samples, the current density decreased sharply, and the sample became resistive just before the breaking point.

The 15-tesla, 15-centimeter-bore solenoid consists of 22 modules, or subcoils, and energy sinks as shown in figure 6. These modules (one of which is shown being wound in fig. 7) were designed to withstand not only the forces which are encountered in their self-field but also the forces developed when the solenoid is placed in external fields in the form of magnetic bottles used for plasma physics experiments. The energy sinks absorb some of the energy released when the magnet returns to the normal state. The performance of the magnet is shown in figure 8, where the field is plotted as a function of position. The charging time is designed to be 5 to 7 hours, and the current is supplied by four 100-ampere power supplies. Since the time required to cool down and to charge the coils is quite long, it is anticipated that the coils will be kept cold and charged somewhere near capacity at all times.

The control circuitry provides for automatic as well as manual control of the charging and discharging rate. Instrumentation is included within the windings to monitor both the magnetic field and the temperature and the stress on the conductors.

In addition to the 15-tesla, 15-centimeter-bore solenoid, a 10-tesla, 6.25-centimeter-bore magnet with better uniformity was built of niobium stannide superconductive ribbon, similar to that described in table I. This solenoid, however, was designed to have a homogeneity of 0.2 per-

cent within a 2.54-centimeter-diameter spherical volume and of 0.7 percent within a 5.08-centimeter-diameter spherical volume.

This magnet, which will be used in the research program of Lewis Research Center, is capable of being charged from zero field to full field in less than 30 minutes. In the semipersistent mode, the maximum critical field decay is less than 500 gauss per hour.

Initially, the magnet will be applied to solid-state physics research, which will include magnetostriction measurements on copper, and magnetoresistance of very pure and also very dilute alloys of aluminum, copper, and bismuth.

Magnetic Bottle

A system of coils whose combined field is shown in figure 9 was built for plasma containment experiments. The system consists of two mirror coils that produce 5 teslas each on the axis of the system and a mirror ratio of 2:1 with the central field. The more uniform central field is provided by inserting a third coil between the two mirror coils, as shown in figure 9. In addition, a cusp field is produced by a system of linear conductors (Ioffe bars⁽¹⁶⁾) equally spaced around the inner diameter of the coil forms. This scheme produces a minimum B field which is more effective than the simple mirror field for plasma containment.

A photograph of the actual coil is shown in figure 10(a) and the winding scheme of the Ioffe coils is shown in figure 10(b). These Ioffe coils are wound with Nb_3Sn (copper clad for stability). They operate quite satisfactorily and are not easily driven to the normal state.

The three main coils are wound with a seven-strand Nb-0.25 Zr cable which is copper plated and dipped in indium. This quasi-stabilized material is easy to handle and wind into coils. Between turns, insulation is provided by a Mylar film, and aluminum foil provides an energy sink to absorb some of the energy when the coils are driven normal. Monofilament nylon threads (0.05 cm in diameter) are wound back and forth across the windings to provide passages for the liquid helium to penetrate the windings. The complete magnet is shown in the photograph of figure 11.

The performance of the system of coils is best described by showing the variation of coil current as it is increased with time. Figure 12 shows that a mirror coil can be charged in less than 2 minutes and that the design field of 5 teslas was achieved.

To provide for improved performance of the coils, it is planned to substitute for the seven-strand NbZr conductor a fully stabilized NbTi conductor to provide for greater stability and better performance of the coils.

In addition to the magnets previously described, there are in use at the Lewis Research Center several other superconductive magnets.

These are single solenoids and split pairs, ranging in size from 2 to 20 centimeters in inner diameter and having field strengths from 2.5 to 10.0 teslas. These magnets and magnet pairs are being used in solid-state, nuclear, and plasma physics research. The research as well as the facilities have been described in available NASA publications^(17 to 18). These magnets are all examples of the type of low-cost magnetic-field equipment which has been made possible by the advent of high-field superconductive materials and the consequent elimination of the high-cost power supply and cooling water supply required by conventional copper magnets.

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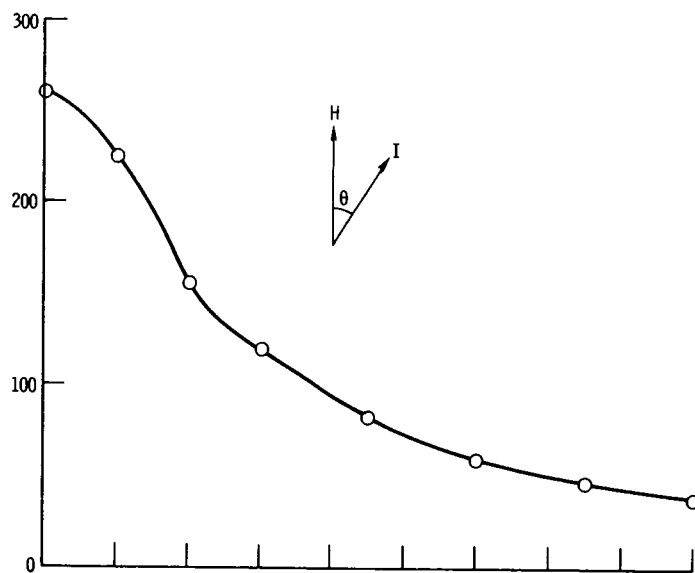
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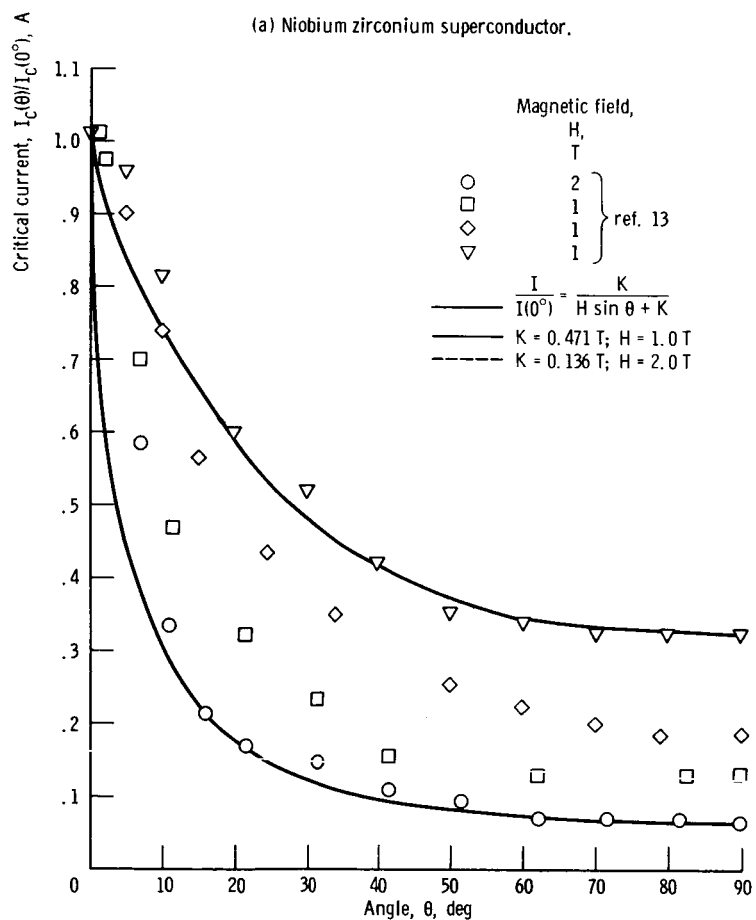
TABLE I. - PHYSICAL PROPERTIES OF NIOBIUM

STANNIDE STAINLESS STEEL RIBBON

Property	Stainless steel substrate	Niobium stannide superconductor
Width, cm	0.23	0.23
Thickness, cm	0.008	0.001
Length, km	88	88
Current density, A/cm ²	- - -	10 ⁶
Tensile strength, N/m ²	16×10 ⁸	16×10 ⁸ (without damage to super- conductor)

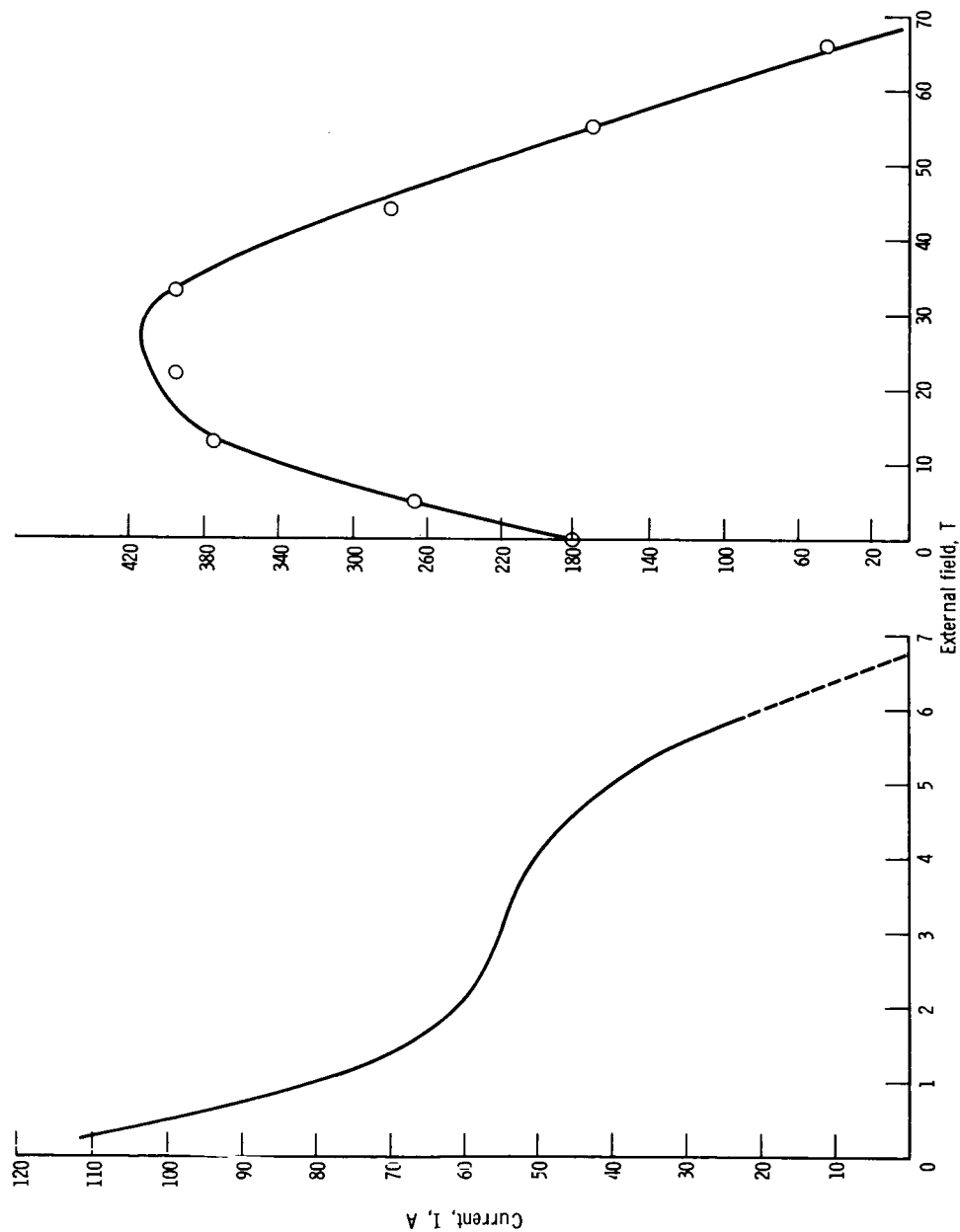


(a) Niobium zirconium superconductor.



(b) Niobium stannide superconductor.

Figure 1. - Critical current as function of angle made by conductor with magnetic field. Sample, 0.025-centimeter-diameter niobium - 0.25 zirconium wire, magnetic field, 3 teslas; temperature, 4.2° K (ref. 19).



(a) Sample oriented transversely to magnetic field.

(b) Sample oriented parallel to magnetic field.

Figure 2. - Typical curve of short-sample critical current field. Sample, 0.25-centimeter-diameter zirconium wire; 0.0025-centimeter electrolytic copper; temperature, 4.2° K (ref. 19).

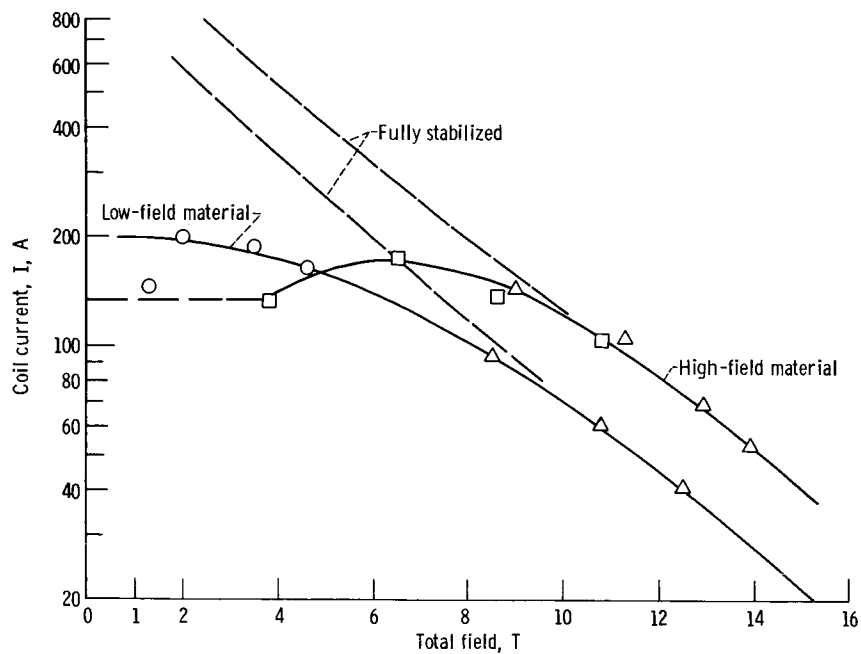


Figure 3. - Critical-current magnetic-field characteristics of niobium stannide ribbon (ref. 17).

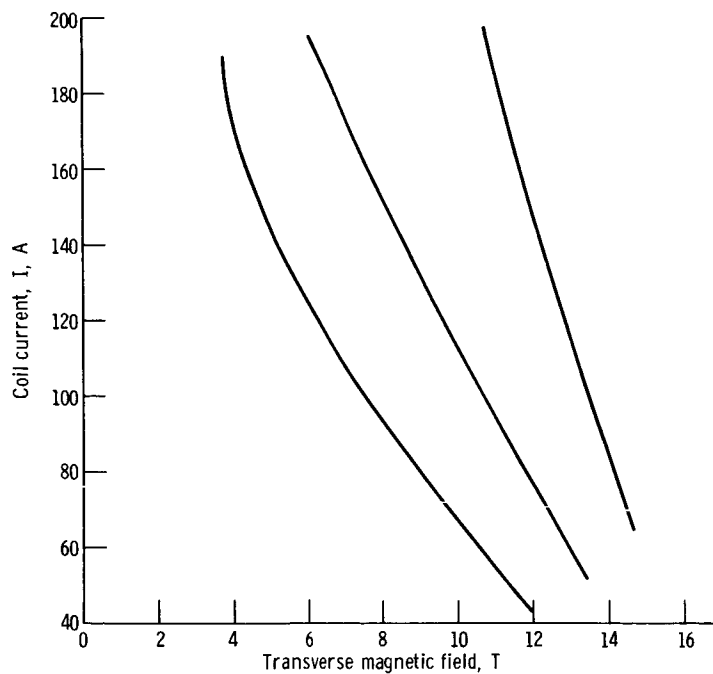
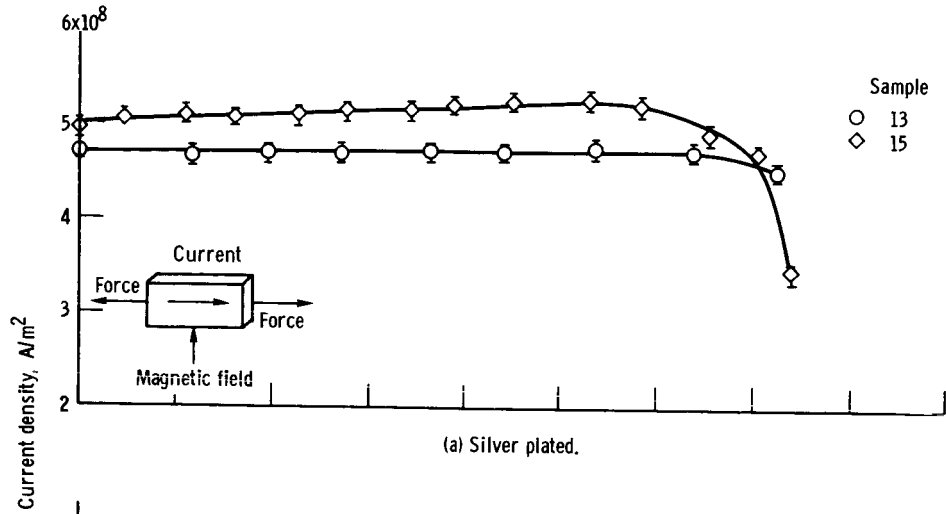
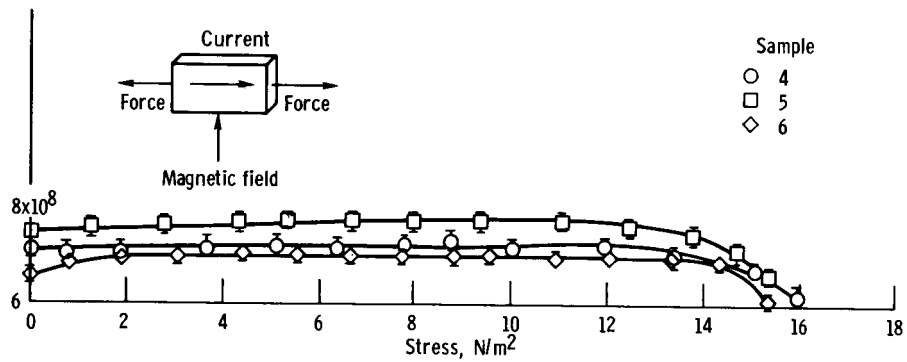


Figure 4. - Ranges of application of minimum-stabilized superconductive ribbon (ref. 17).



(a) Silver plated.



(b) Copper plated.

Figure 5. - Effect of stress on current density of niobium stannide ribbon oriented with magnetic field perpendicular to current in plane of ribbon.



Figure 6. - Components of 15-tesla magnet.

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Figure 7. - Module of a 15-tesla magnet being wound.

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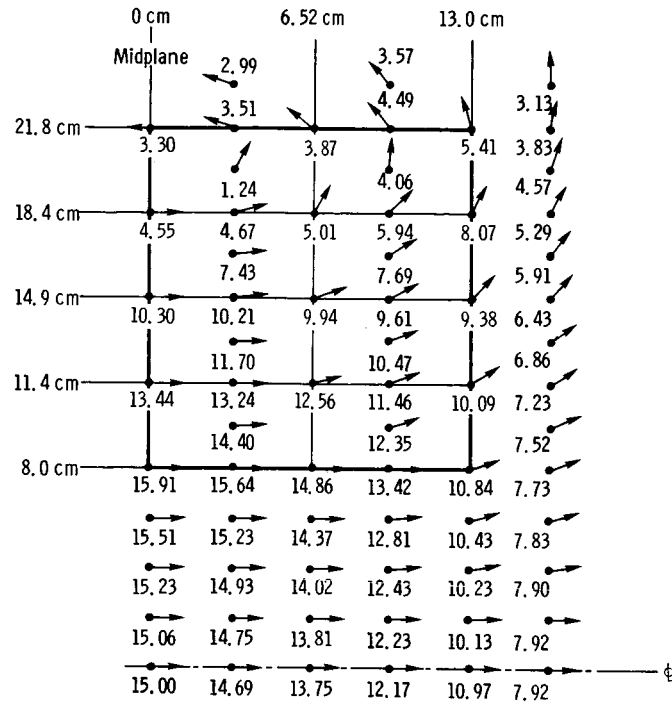


Figure 8. - NASA 15-centimeter-bore, 15-tesla (150 kG) magnet.

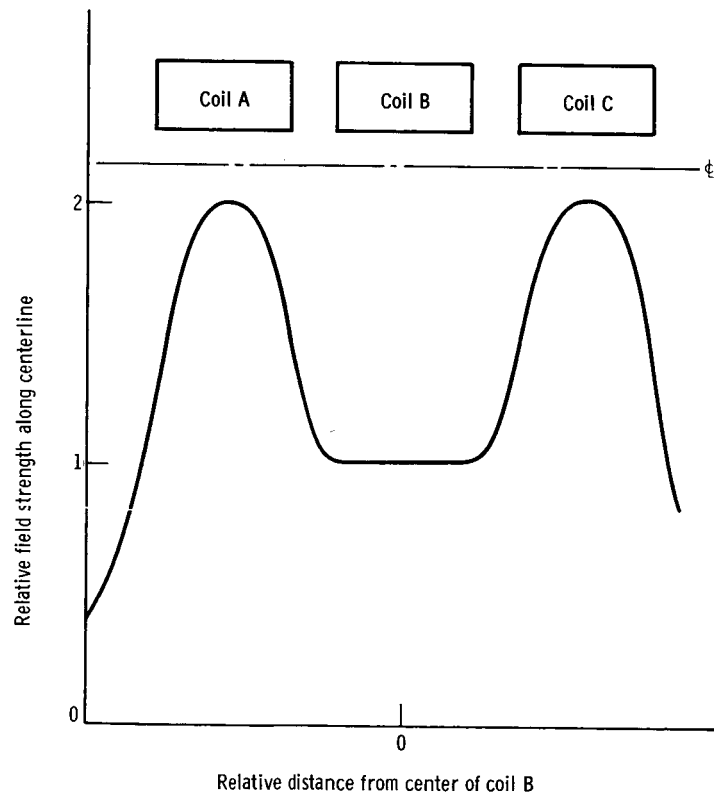
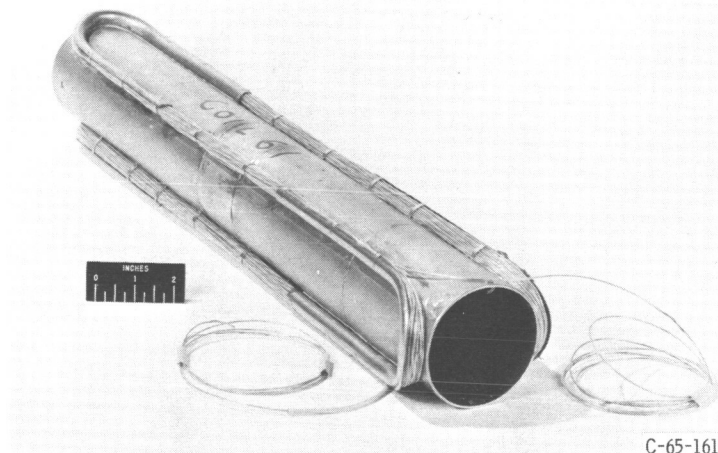
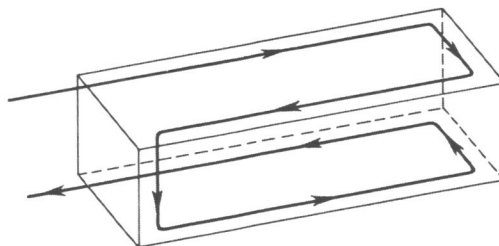


Figure 9. - Magnetic mirror configuration for plasma physics experiments.



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(a) Ioffe coils.



(b) Schematic of current path in coil.

Figure 10. - Ioffe bars (quadrupole configuration).

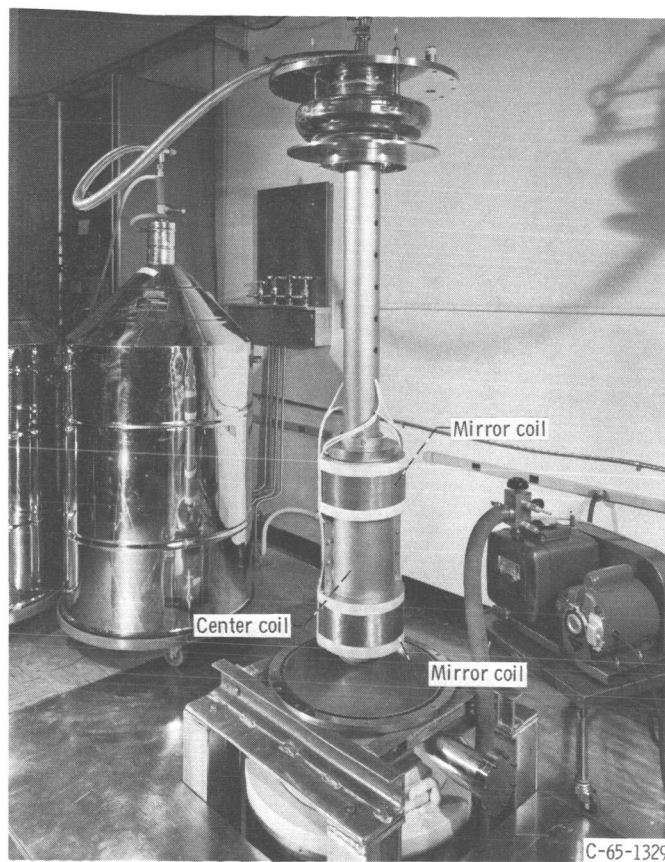


Figure 11. - Magnetic bottle.

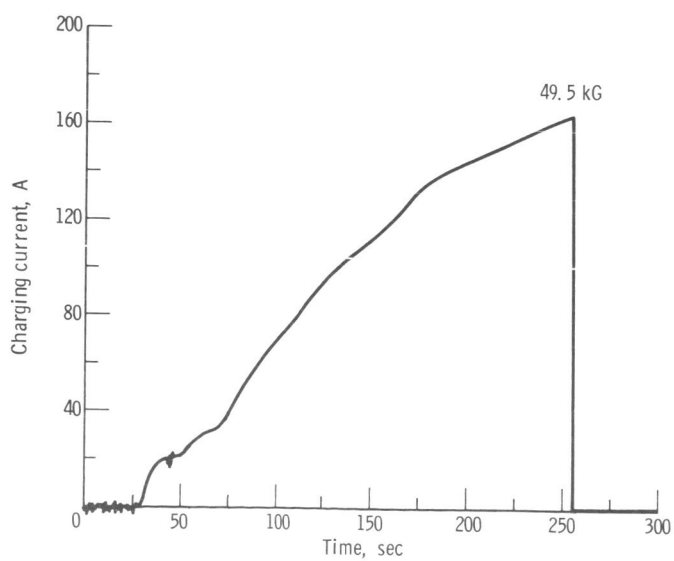


Figure 12. - Charging history, coil A alone.